NANO AIR VEHICLES
A TECHNOLOGY FORECAST

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Preface

For some people, the study of the future brings up images of Nostradamus sitting in a dark room peering into a glowing blue orb foretelling the secrets of the future. Inevitably, any discussion of Nostradamus leads to a list of those things he got right and those he got wrong in his 942 quatrains. But what if he was right even some of the time? Few would argue against having knowledge of what will occur in the future, since this knowledge could lead to actions either to benefit from or avoid something in the future. The study of the future is not about *predicting* the future like Nostradamus, but rather it is a process to discern what is reasonably *possible* in the future and should not be judged if the forecast was right or wrong but by the arguments, for and against, discovered during the process. Thus, this paper is about a technology forecast and the arguments for and against. The value is not simply the date forecasted but it is the description of the challenges that must be overcome and potential ways success may be achieved to make the forecast come true. That is the information we seek as leaders and decision makers.

I would like to acknowledge the anonymous participants who were willing to take time from their busy schedules and provide me with their insightful ideas and reasons behind their forecasts. Finally, nothing I do in the service of the Air Force is possible without the continual support of my wife Corinne as she commands the home front and raises our son Alek, who at 2, had no idea why his father always had his laptop on his lap instead of him. Thank you both.

Abstract

This paper documents the result of a future technology forecast study to determine when operationally useful nano aerial vehicles or NAVs will be achieved. This was accomplished as part of the Blue Horizons Research Team tasked by the Chief of Staff of the United States Air Force to explore emerging technologies and make recommendations for long range investment. This study utilized a future forecasting method called the Delphi Method which was developed by the RAND Corporation in the 1960s to make the forecast. The results indicate NAVs capable of operating in swarms will be available within 10 years to perform operational missions. This paper recommends the Air Force begin work now to fully develop operational concepts and requirements for NAVs to guide future development work and enter the Joint Capabilities and Integration Development System to fully define capability requirements for swarming NAVs across the services to gain efficiencies in development and acquisition of these systems and to avoid duplicative requirements and programs.

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Part 1

Introduction

Who among us would not be glad to lift the veil behind which the future lies hidden; to cast a glance at the next advances of our science and at the secrets of its development in future centuries?.

—David Hibert
Second International Congress of Mathematicians
Paris, 1900

The Technology Force

The United States Air Force is known as our nation's technological fighting force and has come to rely on this technological superiority to win our nation's wars. Examples of the pursuit of technology to create advantages in warfare exist throughout the Army Air Corps and Air Force history. From the development of the Norden bombsight and it's massive employment in the high altitude daylight precision bombing campaign over Europe during WW II, to the rapid development and employment of precision laser guided bombs during the Vietnam War, the Air Force is on a continual quest to seek out emerging technologies and understand how to employ them in war. Fast forward to today and this quest is clearly seen in the F-22A with its stealth technology and advanced integrated avionics suite and again in the design and production of the Joint Strike Fighter or F-35. A well planned, well funded, and well executed strategic technology investment program was required to make these systems possible. In the case of weapons systems like the F-22A and the F-35, this investment required a commitment over decades to achieve.

The CSAF Directive

It has been over 10 years since the USAF executed a long-range assessment "…to examine the concepts, capabilities, and technologies the United States will require to remain the dominant air and space force in the future."[1] The previous effort culminated with the publication of the *USAF 2025 Study* in 1996. The Chief of Staff of the Air Force (CSAF) has directed a long-range assessment of emerging technologies to help guide the Air Force's strategic planning, investment, and capability decisions that may be relevant for future warfare scenarios. The CSAF's goal goes beyond accomplishing just another long-range assessment and includes changing the culture of the planning process ensuring the long view is taken every year to help guide the Air Force positions within the Quadrennial Defense Review and annual budget requests. A part of this effort is an ongoing examination of emerging technologies and accelerated technological change undertaken at Air University by Air Command and Staff College and Air War College students called Blue Horizons.[2]

Blue Horizons

The focus of the Blue Horizons research team was on the rapidly advancing technology areas of biotechnology, nanotechnology, robotics, information technology, and directed energy. Moreover, the team examined the potential for interaction between these technology areas and the resultant implications for the USAF. The team set out to examine specific systems, within and across these technology areas that may be possible within the next 25 years. This examination was accomplished by using various future research methodologies to provide a forecast and investment recommendation to Air Force leadership.

The future technology of interest for this research paper was the potential development and use of a class of unmanned aerial vehicles (UAVs) called nano-air vehicles or NAVs. Chapter 2

of this paper describes the NAV and why it is of interest to the USAF as well as describes the challenges associated with development of these vehicles. Chapter 3 then describes the future research methodology called the Delphi Method used to obtain the forecast and focuses on the strengths and weaknesses of this method as well as provides general sociological data on the study participants. Chapter 4 provides the results and analysis of the research using the Delphi Method which includes the forecast and discussion/analysis of specific challenges that must be overcome to achieve the forecast. Finally, chapter 5 presents the implications to the Air Force of this forecast and makes several recommendations to Air Force leadership.

Notes

[1] *Air Force 2025*, August 1996, ii; on-line, Internet, available from http://www.au.af.mil/au/2025/index2.htm.

[2] "Blue Horizons Syllabus," (Research team course syllabus, Air Command and Staff College, n.d.), 1.

Part 2

Why Nano-Air Vehicles

An insurgent sniper sits in a third-story window on what appears to be a quiet city block to the Army Reconnaissance Platoon slowly moving from building to building on the street below. Suddenly a member of the platoon is struck down by the sniper and the platoon rushes for cover dragging their comrade to safety. The platoon leader looks at the sniper's location and determines he cannot call in an air strike since even if the Air Force used a Small Smart Bomb the explosion could kill too many innocents living in the building. Instead the platoon leader opens a small case with a keyboard and screen and begins typing in commands. Once he hits the execute key, 50 tiny vehicles lift out of the case and immediately begin flying in a swarm at surface level towards the sniper's building. The vehicles, smaller than a dragonfly, vertically ascend the outside of the structure and surround the window of the sniper and wait. When the sniper reappears, the swarm strikes much like a swarm of mosquitoes would, but the sting is considerably stronger and the vehicles propel themselves at the sniper and explode. The platoon leader smiles, the threat has been eliminated and innocents are left with their homes and lives intact, which means the death of one insurgent did not result in many more being created.

—Potential scenario for use of NAVs

What is a NAV?

The definition of a NAV comes from the Defense Advanced Research Projects Agency (DARPA) program under the same name. DARPA defines the NAV "as airborne vehicles no larger than 7.5 cm in length, width, or height, capable of performing a useful military mission at an affordable cost and gross takeoff weight (GTOW) of less than or equal to 10 grams."[1] The NAV dimensions place it in the smallest class of UAVs, per Table 1, which provides a relative scale of various UAV classes and lists characteristics and examples for each class. The DARPA program is the first step to explore the NAV category to determine the efficacy of current and future technology to design and build such a small platform and to explore the characteristics and

potential missions of NAVs. Thus, in Table 1, there are no known systems produced and the example missions are listed as speculative.

Table 1. UAV Classifications[2]

Categories	Abbreviation	Data link Range (km)	Endurance (hours)	Maximum Flight Altitude (m)	Launch Method	Recovery Method
Tactical UAVs						
Nano		Unknown	Unknown	Unknown	Unknown	Unknown
Example Missions: speculative. Example Systems: none known.						
Meso		Unknown	Unknown	Unknown	VTOL	Belly Expendable
Example Missions: wide-area sensing (in swarms), planetary exploration. Example Systems: Mesicopter						
Micro	µ	< 10	1	250	H/HL/VTOL	Belly, skids Expendable
Example Missions: RSTA, comms relay, scouting, NBC sampling, EW. Example Systems: MicroStar, Hyperav+, Black Widow, Microbat.						
Mini	Mini	< 10	< 2	250	HL/L/VTOL/ Wheels	Belly, skids Wheels Parachute
Example Missions: film and broadcast industries, agriculture, pollution measurements. Example Systems: Aerocam, RPH2+, R50+, Rmax+, SurveyCopter.						
Close Range	CR	10-30	2-4	3,000	HL/L/VTOL/ Wheels	Belly, skids Wheels Parachute
Example Missions: Recon, EW, artillery correction, mine detection, search & rescue. Example Systems: APID+, Camcopter+, Cypher, Dragon, Javelin, Luna, Mini Tucan, Mi-Tex Backpack, Observer, Pointer, Vigilant, Vigiplane						
Short Range	SR	30-70	3-6	3,000	L/VTOL/ RATO	Belly-skids Parachute/airbag
Example Missions: RSTA, BDA, EW, NBC sampling, mine detection Example Systems: Crecerelle, Dragon, Eyeview, Fox, Heliot+, Mirach 26, Phantom, Phoenix, SoOJKY, Sperwer, Vulture						
Medium Range	MR	70-200	1	3,000-5,000	L/VTOL/ Wheels/ RATO	Skids Wheels Para/airbag
Example Missions: RSTA, BDA, artillery correction, EW, NBC sampling, mine detection, comms relay Example Systems: Brevel, CL327+, Eagle Eye+, Mucke, Outrider, Pioneer, Prowler, Ranger, Searcher, Seeker, Sentry, Shadow 200, Skyeye, Sniper						
Low Altitude Deep Penetration	LADP	> 250	1	0.12-9,000	RATO	Para/airbag
Example Missions: Recon. Example Systems: CL89, CL289, Mirach 100, Mirach 150						
Long Range	LR	> 500	6-13	5,000	Wheels/ RATO	Wheels
Example Missions: RSTA, BDA, comms relay. Example Systems: Hunter						
Endurance	EN	> 500	12-24	5,000-8,000	Wheels/ Launcher	Wheels Para/airbag
Example Missions: RSTA, BDA, comms relay, EW, NBC sampling Example Systems: Aerosonde, Hermes 450, Prowler II, Searcher II, Shadow 600, Super Vulture						
Strategic UAVs						
Medium-Alt. Long-Endurance	MALE	> 500	24-48	5,000-8,000	RLG	RLG
Example Missions: RSTA, BDA, comms relay, EW weapons delivery Example Systems: Altus, Hermes 1500, Heron, I. Gnat, Perseus, Predator, Theseus						
High Altitude Long Endurance	HALE	> 1,000	12-40	15,000-20,000	RLG	RLG
Example Missions: RSTA, BDA, comms relay, EW, boost phase intercept launch vehicle. Example Systems: GlobalHawk, Raptor, Condor						
Special Purpose UAVs						
Lethal		300	4	3,000-4,000	Launcher/RATO/ Air-Launch	Expendable
Example Missions: Anti-tank/vehicle, anti-radar, anti-infrastructure, anti-ship, anti-aircraft Example Systems: Harpy, K100, Lark, Marula, Polyphem, Taifun, Sea Ferret, MALI						
Decoys		0-500	<1 to few	30-5,000	Canister/ RATO/ Air-Launch	Expen dable
Example Missions: Aerial and naval deception. Example Systems: Chukar, Flyrt, MALD, Nulka						
Acronyms: BDA: battle damage assessment L: launcher RSTA: recon, surveillance, target acq EW: electronic warfare NBC: nuclear, biological, chemical VTOL: vertical take-off & landing H: hand-launched RATO: rocket-assisted take-off HHL: hand-held launcher RLG: retractable landing gear						

The DARPA NAV program exemplifies the progress made in the miniaturization of UAVs. Just a few years ago, groundbreaking research was underway in Micro-UAV (MAVs) which are defined as UAVs with wing spans less than 6 inches. Today, useful MAVs are a reality as

demonstrated by the successful operation of the AeroVironment *Black Widow* MAV as part of a DARPA Small Business and Innovative Research program. The *Black Widow,* seen in Figure 1, is capable of over 30-minute flight endurance and can down link full color video to the operator all in a package with a wingspan less than the length of a pencil.[3]

Figure 1. The AeroVironment Black Widow.[4]

The DARPA NAV program seeks to push the technology threshold for UAVs beyond the gains demonstrated with the *Black Widow*. The DARPA program is focused on the design and development of an air vehicle capable of autonomous operation to facilitate intelligence and surveillance operations in a restricted urban or interior environment. The NAV program seeks to stimulate research in the field to overcome many of the technology challenges facing the development of an air vehicle this size capable of useful military missions in the future and to demonstrate this system in both an indoor and outdoor environment.[5] The diminutive size and weight of the NAV requires advancements in aerodynamic design for low Reynolds number airfoils, lightweight and efficient propulsion and energy storage systems, autonomous guidance,

navigation, sensors and communication subsystems, and advanced manufacturing techniques to achieve the high level of system integration required.[6]

Technology Challenges

Aerodynamics

Aerodynamic design challenges for NAVs are driven by a combination of low Reynolds number physics (<15,000) and the requirement for a multi-functional platform structure.[7] These challenges have already motivated many novel approaches for NAV designs such as flying-wing designs as already demonstrated with the *Black Widow* MAV, rotary wings or biologically inspired designs with flapping-wings like hummingbirds or insects or even maple tree seeds.[8] Fortunately, these challenges are similar to the aerodynamic challenges overcome with MAVs and researchers can build upon this knowledge; however, the limited volume of space available within the NAV structure makes the aerodynamic challenge even greater than that overcome by MAVs.

Propulsion and energy storage

Propulsion and energy storage systems for NAVs will require a highly efficient power source with sufficient energy and power density to fly and execute relevant missions.[9] Even more challenging is the requirement for very dense energy storage that can be efficiently converted to thrust to propel the vehicle as well as power all the subsystems.[10] For propulsion, several alternatives under investigation include electric motors, micro-turbines, and chemical muscles. In all cases, the challenge is to generate and store enough energy for both propulsion and other subsystems. The use of bio-inspired chemical muscle is quite novel and would have

the ability to gather fuel from the environment much like a bird and continue to execute the mission. [11]

Guidance, navigation, sensors, and communications

The previously described challenges with structural design and energy generation and storage make the technology challenges even greater for the guidance, navigation, sensors and communications systems. Furthermore, if NAVs are required to operate autonomously and in "swarms" then the challenge is made even greater due to the much larger processing and sensory requirements these operations entail.[12] A major technical challenge is to integrate navigation, guidance and control onto a single chip to meet the restrictive size, weight and power requirements driven by the NAV vehicle design. In the case of NAVs, the size of these systems may reach microscopic or nanoscale to meet the strict requirements driven by the size of the vehicle.

Advanced Manufacturing

From the discussion above, it is obvious the NAV requirements drive towards highly integrated subsystems with innovative configuration layouts at very low weights. New manufacturing techniques in all areas from batteries to sensors are required to achieve a NAV. This technology challenge is a key component of the DARPA NAV program which made the requirement to demonstrate a clear process to integrate other subsystems into the airframe and show the capability to manufacture the system.[13] This technology area will benefit greatly from advancements in nanoscale fabrication techniques which were predicted in the 2002 USAF Science and Technology Board report on implications of emerging micro- and nanotechnologies.[14]

Potential Missions

The predominant mission of UAVs today is primarily the Intelligence, Surveillance, and Reconnaissance (ISR) mission as seen with the Predator and Global Hawk UAVs as well as the plethora of smaller UAVs currently in use by all the services. The utility of UAVs for strike missions was clearly seen with the Predator in Operations ENDURING FREEDOM and IRAQI FREEDOM. This was such a success the Air Force followed the Predator with the development and rapid fielding of the MQ-9 Reaper which was purpose built for ISR and strike missions.[15] The advent of MAVs and NAVs in future wars can bring capabilities not seen in today's UAVs due to advances in robotics, nanotechnology, advanced explosives, and advanced manufacturing techniques. The question becomes what missions these much smaller UAVs will be capable of executing.

ISR Missions

The dominant mission application area for UAVs will continue to be ISR missions; however, NAVs will enable expansion into new exploitation domains. The small stature of these vehicles combined with vertical flight and autonomous capability will enable their use in urban operations much like was portrayed in the opening vignette of this chapter. ISR operations within buildings, tunnels, caves and other formations that are currently only accessible by man will become possible for ISR exploitation with NAVs.[16] The combination of small size, precision delivery, and multi-spectral sensors will provide commanders effective ISR of areas that typically put combat soldiers or airmen at risk to exploit.

NAV designs under consideration include vehicles that mimic large flying insects or very small birds that can fly and land inside buildings or tunnels and transmit images. These designs could also land and lie dormant until programmed sensors detect movement or chemical tracers

of intended targets and begin transmitting data of what they found. These types of vehicles could be launched from soldiers on the ground or even from guided cluster bomb units launched from larger UAVs or manned aircraft into the region of interest. The small size of these vehicles provide natural stealth and deployed in large numbers can provide large area coverage at low cost due to their low overall acquisition costs compared to larger UAVs or manned systems.[17]

NAVs combined with advanced sensors will provide commanders will unprecedented ISR flexibility. Nanotechnology could provide extremely small and accurate Nuclear, Biological, and Chemical (NBC) sensors that NAVs can employ. Miniature chemical detectors the sizes of individual molecules are already under development. Each detector is purpose built to detect specific molecules or even protein markers for biological agents. These molecular or protein sensors deployed into tiny arrays carried by NAVs could provide extremely accurate detection of NBC contaminants. Deployed in swarms, these NAVs could quickly identify the type of contaminant and spread out to determine the extent of the contaminated area and report back to commanders.[18] As the sensor technologies mature, NAVs could provide commanders incredible flexibility to execute difficult ISR missions covertly with low risk to friendly forces.

Offensive Counter Air (OCA)

NAVs combined with swarming operations could provide some ability in OCA missions. Direct attacks against flying aircraft would be very difficult due to the relatively slower speed of NAVs; however, attacks against aircraft located on the ground are possible. This could be accomplished either by employing NAVs equipped with mini-explosives or through foreign object damage by the vehicles purposely flying into the aircraft.[19] However, the natural stealth of these vehicles combined with advanced sensors could prove very useful in suppression of enemy air defense (SEAD) missions.

SEAD missions are very dangerous and make a natural mission area for UAVs to take over in the future as air defense technology continues to advance. The spread of relatively cheap and quite effective air defense technology makes this a very dangerous mission for manned aircraft that the USAF will likely face in the future in even relatively small conflicts. NAVs equipped with mini-explosives and operating in swarms could quickly overwhelm the integrated air defense (IAD) and strike at sensitive search and targeting radar sites to bring down the IAD system of the enemy. Explosives may not even be necessary since a large swarm of NAVs could form an electromagnetic barrier around sensitive IADS sensors and temporarily disable the sensor while an attacking force flies through the coverage area.[20] Regardless of method, explosives or electromagnetic, the effect is the same. The IADS would be knocked out to allow a larger attacking force through.

Close Air Support (CAS)

The vignette presented at the beginning of this chapter is a good example of the force multiplier a swarm of NAVs would provide to ground units in either urban or open terrain. The use of NAVs against small units or individuals would provide precise effects to unit commanders on the ground without extensive collateral damage or risk for fratricide incidents. These NAVs could be used in hunter-killer operations by continually screening the area around a ground force and when an enemy is identified they can quickly attack and neutralize the targets. The swarming NAVs would give the ground commander both precise and effective firepower that they can apply at will.

Strategic Attack

Much like the OCA, SEAD and CAS missions, NAVs could prove very useful for attacking targets that make up an enemy's Center of Gravity (COG). The enemy's COG could be anything

from their power grid to command & control nodes which NAVs could be effective. In a force on force conflict, strategic targets are typically well defended and usually deep behind the enemy's front lines. Thus, a long range platform is typically required to reach them.[21] Present technology limits the range of NAVs to very short distances due to energy storage and propulsion efficiency problems that must be overcome. A large portion of the ongoing research for these vehicles is in the energy storage and propulsion area. Until these limitations are overcome, NAVs would require other modes of transportation, such as being dropped in a cluster bomb unit from a larger air vehicle, to reach the intended targets.

Other Missions

Swarms of NAVs could also act as mobile mine fields around units. The NAVs would remain dormant using only the sensor suite to determine if the enemy is encroaching on the unit's position. Once an enemy encroachment is identified, the ground commanders can be notified, and commands to the swarms could be sent to either let the forces through or to 'awaken' and attack the encroaching force. The NAV mine field is mobile since it can move with the ground force as it executes it assigned missions in the hunter-killer mode previously discussed. This application also can benefit USAF security forces to execute the airbase defense mission.

Notes

[1] Defense Advanced Research Projects Agency (DARPA), *BAA 06-06 Proposer Information Pamphlet: Nano Air Vehicle (NAV) Program*, (Washington D.C.: Defense Sciences Office, 2006), 4. on-line, Internet, available from http://www.darpa.mil/dso/solicitations/BAA06-06_sect2.pdf

[2] Arthur F. Huber, *Death by a Thousand Cuts: Micro-Air Vehicles (MAV) in the Service of Air Force Missions*. Maxwell AFB, AL, Air War College, 2001, 5.

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[3] Mr. Sam Wilson. Defense Advanced Research Projects Agency (DARPA) , Tactical Technology Office (address, DARPATech 2000 Symposium, Anaheim, CA, 31 Jul 2002). On-line, Internet, available from http://www.darpa.gov/DARPATech2002/presentations/tto_pdf/speeches/WILSONSB.pdf

[4] Mr. Sam Wilson.

[5] Defense Advanced Research Projects Agency (DARPA), *BAA 06-06 Proposer Information Pamphlet: Nano Air Vehicle (NAV) Program*, (Washington D.C.: Defense Sciences Office, 2006), 5. on-line, Internet, available from http://www.darpa.mil/dso/solicitations/BAA06-06_sect2.pdf

[6] Press Release, "DARPA Launches Nano Air Vehicle Program." Defense Advanced Research Projects Agency, Dec 2006. on-line, Internet, available from http://www.darpa.mil/body/news/current/index.asp

[7] Ibid.

[8] Ibid.

[9] Defense Advanced Research Projects Agency (DARPA), *BAA 06-06 Proposer Information Pamphlet: Nano Air Vehicle (NAV) Program*, (Washington D.C.: Defense Sciences Office, 2006), 5. on-line, Internet, available from http://www.darpa.mil/dso/solicitations/BAA06-06_sect2.pdf

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[14] Department of the Air Force, *Implications of Emerging Micro- and Nanotechnologies*, (Washington D.C.: Air Force Science and Technology Board [Committee on Implications of Emerging Micro-and Nanotechnologies], 2002), on-line, Internet, available from http://books.nap.edu/books/030908623X/html/183.html#pagetop, 212.

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[16] James F. Abatti, *Small Power: The Role of Micro and Small UAVs in the Future*. Maxwell AFB, AL, Air Command and Staff College, 2005, 29.

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[18] James M. McMichael and Col. Michael S. Francis, *Micro Air Vehicles - Toward a New Dimension in Flight*, Defense Advanced Research Projects Agency, on-line, Internet, 10 January 2005, available from http://www.darpa.mil/tto/mav/mav_auvsi.html, n.p.

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[20] James F. Abatti, 31.

Notes

[21] Arthur F. Huber, 49.

Part 3

The Delphi Method

Foreknowledge of the future makes it possible to manipulate both enemies and supporters
— Raymond Aron in *The Opium of the Intellectuals*

Background

One of the first modern technology forecasts was executed by the RAND Corporation in the early 1960s using a method called the Delphi method.[1] The Delphi method is a systematic way to obtain opinions from a panel of experts and obtain consensus without group discussion. This method avoids external influence in the debate of committee activity or group think by using a series of questionnaires to individual panel members who are promised anonymity. The goal of this technique is to achieve a forecast without the influence of "…certain psychological factors, such as persuasion, the unwillingness to abandon publicly expressed opinions, and the bandwagon effect of majority opinion."[2] RAND's interest in the study of the future, and in particular the development of the Delphi method, legitimized forecasting. A simple literature search reveals the extent of RAND's influence since this study was published with governments, non-governmental organizations, to public and private corporations using the method to forecast the future.

Procedure

The first step in the Delphi method is identifying the participants and asking them to participate in the study. The participants include experts in the field as well as others who have expressed negative opinions about the subject matter to provide balanced opinion. The

participants are assured anonymity so none of the statements are directly attributed to them by name. The researcher then builds the first questionnaire which usually requests each participant to provide a date at which some technology will be available and state the reasoning behind this date. After the responses are received, the researcher analyses the range of responses and presents this range to the group. If necessary, participants with opinions on the outside of the norm are requested to provide the reasons behind their position. This cycle continues until a group consensus is met, or for those participants that cannot agree, their reasons are made clear. However, history shows most expert groups move towards consensus.[3]

The information obtained from a Delphi study is useful with or without consensus which provides a policy maker with valuable information about the future; however, there are several weaknesses of this method. The first is the amount of time it takes to accomplish. A single round can take at least 3 weeks which makes a 3 round Delphi a 2.5 month effort without the final analysis and report preparation period. The second weakness is some Delphi studies are self fulfilling or biased due to a limited span of participants. Care must be taken to ensure experts in the field under examination are chosen as well as participants who are more skeptical to encourage full and clarity of the reasons behind a forecast. Finally, the last weakness is the question asked. The researcher must ensure the question is clear and unambiguous. A question that merely asked for a simple forecast is limited in usefulness; however, a forecast with in depth opinions of the experts on how this may be achieved and actions that could accelerate or delay the achievement is where the power of the Delphi method lies.[4]

For this study, over 40 people were invited to participate. The professions and background of these people included military and civilian personnel, academia working in one of the technology areas challenged by the NAV, or industry professionals with some background in

related industries. Most of the personnel invited to participate had over 20 years experience and were considered experts in their field. In the interest to maintain some balance of thought in the study, an effort was made to invite less experienced people that were just starting their careers in the related technology areas. In this case, several post-doctorate and doctorate-candidate students were invited to participate in this study.

In the interest of time, only two rounds of questionnaires were used to complete this study. Both questionnaires are included in the appendices of this paper. Since only two rounds were utilized due to time constraints, if additional clarification from the participants was required, the participant was contacted directly to obtain it and their response was modified as required. At the completion of this study only a total of seven full responses were received. Table 2 is provided to show the demographics of these seven participants. Due to the limited responses in this study, additional research was executed to check the validity of the forecast and details contained herein.

Table 2: Delphi study participant demographics

Participant	Employment Type	Specialty	Experience	US/Foreign
1	Government	UAV basic research/engineering	>20	US
2	Academia	Robotics/UAV controls	<10	Foreign
3	Academia/Industry	Avionics/sensors and controls	<10	US
4	Academia	Propulsion	>20	US
5	Academia	Navigation & Controls	>20	US
6	Academia/Industry	Micro mechanical system materials and packaging	>15	Foreign
7	Academia	UAV autonomous controls MAV design	>20	US

Notes

[1] Theodore J. Gordon and Olaf Helmer-Hirschberg, *Report on a Long Range Forecasting Study*, RAND Report, R-2982 (Santa Monica, CA: RAND 1964), n.p.

[2] Jeremy C. Glenn and Theodore J. Gordon, *Futures Research Methodology* Ver. 2.0 ed. (Washington DC: American Council for the United Nations University the Millennium Project, 2003), 3-3.

[3] Ibid.,5.

[4] Ibid., 11-12.

Part 4

The Forecast

Out of the seven final responses, six of the seven agreed that NAVs would be capable of performing military operations using cooperative behavior in swarms within the 10 year time frame. Only one participant indicated they did not believe this capability could ever be achieved due to the technical challenges that must be overcome. This chapter summarizes the reasoning behind these responses and details the likely methods how the technical hurdles could be overcome in the 10 year timeframe. In addition, the opposing view that these vehicles will not be operational in this timeframe is presented.

Majority Opinion

The majority of the respondents indicated that it is possible now to build an air vehicle to the specifications outlined by the DARPA NAV program of 10 gram total vehicle weight including 2 gram payload, 20 minutes duration, 20 knots airspeed, and able to operate in a GPS denied environment. At the present time, this does not include the ability to act cooperatively in swarming formations. In addition, the respondents indicated this size of vehicle would be presently limited to the surveillance type of mission since only a 2 gram payload is possible in this vehicle. All the respondents agreed improvements must be made in guidance, navigation, control and communication systems including advances in autonomous behavior algorithms for swarming operations, energetic materials or explosives, storing energy and efficiently converting it to propulsive power, and finally overall system integration and miniaturization.

The participants were asked to rate in order which of these technical challenges are most difficult to overcome and discuss likely approaches they could be overcome within the forecast period. As a reminder, the Delphi Method provides anonymity to the participants to ensure a full and open discussion is obtained on the subject. To maintain their anonymity, a summary of the results is provided below which do not provide any reference notes. Areas that were researched outside of the participant's discussions are noted as appropriate for proper credit and reference. The technical discussion results are provided in order of difficulty agreed to by the participants.

Guidance, Navigation, Control, and Communication Mechanisms

The future concept of operations for NAVs is very different from anything in operation today since they will be able to operate with an advanced degree of autonomous operation and use cooperative behavior methods to perform missions. This will require NAVs to have advanced sensors, communication, and processing capabilities to handle tasks from flying and navigating to communicating with other vehicles in the swarm as well as any communications to controllers. These subsystems must be highly energy efficient and highly integrated into the air vehicle due to size, power, and energy limitations of a vehicle this size. The challenges in this area can be broken into three general areas: sensing, decision making, and communications.

NAVs require advanced miniature and rugged sensors that enable the vehicle to be completely aware of its surroundings as well as to enable interaction and tracking of other vehicles operating in the swarm. Biologically inspired vision based sensing is one way to provide the sensing capability required for both obstacle avoidance and navigation. One participant believes it is possible now to build 3-D scanning laser radar that would weigh only 1 gram using Micro-Electro-Mechanical Systems (MEMS) technology. This 3-D scanning laser radar would form the basis of a vision-based navigation and control system for the NAV. With

vision based sensors the NAV would be able to see and avoid obstacles as well as navigate through complex regions to include urban environments.

An even more difficult challenge is building the software algorithms to use the sensor and communication information and fuse the data together to implement useable decision or control algorithms for the NAV. Truly autonomous and swarming NAVs will require fundamental research into collective behaviors and data structures along with controls to achieve realistic mission performance in any flight environment. These algorithms will require large amounts of computational power to enable independent decision making based on the information provided by the sensors. This problem is amplified by the requirement to keep both the chip size extremely small but also the power requirements of the processor small. Therefore, both advances in autonomous and swarming flight control algorithms and the development of even smaller and more powerful computer processors are required to enable swarming NAVs.

Embedded communication is also difficult because a well engineered vehicle like a NAV can fly farther than the communications range it can afford from a weight and power budget perspective. In addition, each NAV is a network node and as more NAVs make up a swarm the network of these nodes becomes larger and more complex. This becomes a classic ad hoc networking problem as each node in the network may routinely enter or leave the network. As the swarm navigates to a target the network must be robust and flexible to handle the enormous data load coming from the sensors of each NAV and handle drop outs as a NAV comes in and out of range or even fails. This is a difficult enough problem with large fast moving aircraft let alone for vehicles the size of a NAV.

In summary, the most difficult technology area to overcome to make swarming NAVs a reality is guidance, navigation, control, and communications. Progress in sensory devices and

systems are required to allow the development of advanced navigation, environment sensing and vehicle control systems to achieve the 10 year forecast. In addition, continued progress in low power, high performance computing in smaller and smaller chip sizes is required to execute complex trajectory calculations, ad hoc network communication, and process the information gathered from sensors and communications subsystems. Finally, basic research in collective behavior, data structures and control algorithms is needed to not only control the individual air vehicle but also the collective behavior of the swarm to achieve even basic mission scenarios.

Energetic Materials

To execute kinetic operations the participants indicated the small size of a NAV payload of approximately 2 grams limits the vehicle's lethality. Current explosive technology does not have enough energy density to be useful in most kinetic operations. However, 2 grams of explosive may be sufficient for the anti-personnel mission if an efficient and light method is found to couple this energy into the target. Several participants believe it is possible to couple the equivalent energy of a small arms round into a target utilizing 2 grams of explosive carried in a NAV. To be useful for more kinetic missions, advances in light and highly energetic materials is required.

The study results showed a perception among the participants that there was little investment and focused research in energetic materials research in the United States. Beyond this statement, there was little discussion on the topic since none of the participants had explosive technology backgrounds or were well enough versed in the current state of this technology. A literature review, however, supports their claim the United States and the DOD has placed relatively little emphasis on explosive technology research.[1] In addition, the commercial production base for explosive technology has shrunk significantly per a Commerce Department Study Report which

stated explosives technology development is in a rapid decline and the nation's energetic material infrastructure is at risk unless significant new investment is made.[2] A National Research Council Report goes further to conclude, "Revolutionary, orders of magnitude improvements as measured by increased energy density or increased power are unlikely to occur in the near future."[3]

However, there is some ongoing research within the Department of Energy and DOD to explore the potential of nanoscale energetic materials.[4] The majority of the research is centered on nanomixtures and nanocomposites which typically consist of ordered support matrices with particles of metals, metal oxides, organic or inorganic energetic materials. Nanomixtures and nanocomposites have potential to increase the performance of conventional explosives by increasing the energy density of the explosive. By controlling the composition of the explosive and the supporting nanomatrix, the energy release rate can be controlled which would greatly increase the yield of today's explosives.[5]

Energy Storage and Propulsion

The storage of energy and the efficient conversion to propulsive power is very difficult for a system of this size. The NAV's small size drives the requirement for new high energy density storage that is also highly efficient when transferred to propulsive power and other uses. In general, NAVs with GTOW of 10 grams will require approximately .25 Watts of electrical power for the propulsion system alone, thus, assuming 25% conversion efficiency, a NAV will require about 1 Watt to keep it in the air. This power level is independent of other energy requirements for the other subsystems in the NAV which increases the power generation requirements of the NAV. Batteries, fuel cells, and turbines are potential sources of power, but

advances are required in all of these for a NAV to have sufficient range, speed, and payload to be operationally useful.

System Integration and Miniaturization

Designing and building a NAV will require revolutionary manufacturing technologies to integrate nanoscale components into the airframe itself. The very small size of the airframe along with the other technology challenges already presented drives a classic systems engineering and design problem. Tradeoffs will inevitably be required between propulsion, guidance and control, energy storage, and payload all of which depends on the required capabilities to execute the assigned missions.

Much of the design problem comes down to energy. The NAV is more and more energy constrained the smaller it gets. A major limit to all very small vehicles is the cubed-square law which results in the vehicle volume decreasing relative to the area as size is reduced which results in energy density being limiting at small sizes since there is little space to store fuel. This means that the solutions to propulsion, guidance, navigation, and communication problems cannot make use of traditional relatively power hungry approaches. Thus, further advances in MEMS and nanotechnology is required to further shrink all the subsystems to fit within the limited volume of space provided by a NAV.

Negative Opinion

One respondent maintained that the full vision of man-made swarming NAVs will never be achieved. The argument against the efficacy of the NAV was based on the extreme technical hurdles associated with such a small vehicle size and the requirement to provide sufficient power efficiently to allow a useful mission duration and payload. Furthermore, current and future

battery technology does not offer the required energy density and combustion engines at these small scales are not sufficiently efficient. According to this participant, there was nothing on the horizon that is close to providing the energy densities necessary in this class of air vehicle. This problem coupled with the even more daunting guidance, navigation, control and communications problems led this participant to state NAVs would never be capable of performing useful military missions.

Other Ideas

The problem of energy storage and propulsion led several of the participants to postulate other approaches to this problem. One area of research that may hold promise for this size air vehicle is the use of biological fuel cells for the storage and transfer of power. A biological fuel cell is defined as "a device that realizes the conversion of biochemical energy into electrical energy. The basic principle is that the process of substrate oxidation by microorganisms or enzymes in the fuel cells offers electrons for electricity production."[6] The primary difference between chemical and biological fuel cells is the biological fuel cell uses enzymes or other micro organisms for the catalyst in the reaction. This form of reaction is very attractive for NAVs since the theoretical efficiency of the conversion reaches 90 percent. Thus, future NAVs may gather fuel from the environment and consume it to increase range in operational missions.[7]

Notes

[1] National Research Council Committee on Advanced Energetic Materials and Manufacturing Technologies Board on Manufacturing and Engineering Design Division on Engineering and Physical Sciences, *Advanced Energetic Materials* (Washington, D.C.: The National Academies Press, 2004), 37.

Notes

[2] Department of Commerce, Bureau of Export Administration, Office of Strategic Industries and Economic Security. 2001. *National Security Assessment of High Performance Explosives and High Performance Components Industries*, (Washington, D.C.: 2001), i.

[3] The National Research Council, 37.

[4] Ibid., 24. The laboratories include Lawrence Livermore National Laboratory, Las Alamos National Laboratory, Sandia National Laboratory, the Army Research Laboratory, Naval Air Warfare Center, and Air Force Research Laboratory, Eglin AFB, FL. Only about $8 million is earmarked for nanotechnology research for explosives.

[5] Ibid., 24-25.

[6] Aarne Halme, Xiachang Zhang et al., (2000): *Study of Biological Fuel Cells*, 2nd Annual Advances in R&D the Commercialization of Small Fuel Cells and Battery Technologies for Use in Portable Applications, (New Orleans, LS: April 26-28, 2000) n.p., on-line, Internet, available at http://www.automation.hut.fi/research/bio/sfc00pos.htm

[7] Amy Stone.

Part 5

Implications and Recommendations

Implications

The results of this technology forecast indicate NAVs will be technically capable of operationally useful missions operating in swarms in 10 years. The basic efficacy of the component technologies are now being demonstrated and will undergo rapid development over the next 10 years which will significantly broaden the NAVs capabilities from the limited ISR capability to be demonstrated by the DARPA NAV program. The Delphi Study results are backed up by other studies on this topic to include the Secretary of Defense's UAV roadmap, published in 2002, which predicts UAVs capable of operating as fully autonomous swarms will be available by 2015.[1] The forecast predicts the technology will make NAVs possible but it does not necessarily mean the Air Force or DOD will be ready for them in 10 years. The advent of NAVs capable of cooperative behavior will have broad implications on how the Air Force will use airpower to deliver precise effects upon an enemy.

The capabilities of NAVs cooperatively operating in large swarms will enable the Air Force to utilize lower cost UAVs to perform complex missions not thought of in today's Air Force.[2] These vehicles will be capable of performing complex high-risk missions that today's UAVs are not capable of performing and require manned aircraft to perform. Even more daunting is the possibility these vehicles could be bought or developed by other nations to be used upon our forces in future conflicts. The United States is not alone in the quest for the benefits of nanotechnology among the technologically advanced countries as well as less developed

nations.[3] These nations desire the benefits of nanotechnology for medical and defense related products that many multi-national corporations could provide.

Much of the research and thought of MAVs and NAVs has focused on the underlying technology and methods to achieve the technology; however, there has not been a thorough exploration of the operational implications of cooperative and autonomous swarms within the Air Force. The Air Force should explore the following questions to help guide the development of NAVs to close the gap between technology and system operational requirements.

- What operational missions does the Air Force foresee for NAVs?
- What capabilities from NAVs does the Air Force require to fulfill these missions?
- What are the operational level concepts for the use of NAVs?
- How will command and control of these systems be conducted?
- How do we defend against these weapons?

Recommendations

Failure to answer these questions now will result in unnecessary delays in the development of operationally useful NAVs for the Air Force. The DARPA NAV program is the first step in this process as they push the envelope of current technology to design, build, and demonstrate NAVs for ISR missions. Ongoing developments in robotics and nanotechnology will rapidly expand the potential roles for NAVs with multiple uses from ISR to strike missions. Now is the time for the Air Force to determine what the future requirements are for NAVs and start investment in them to guide their development. Thus, the recommendation is for the Air Force to bring the research and operational communities together to fully explore operational requirements for NAVs for future operations. In addition, the Air Force should lead the other services using the Joint Capabilities and Integration Development System to fully define capability requirements for swarming NAVs across the services to gain efficiencies in

development and acquisition of these systems and to avoid duplicative requirements and programs.

If the operational community determines there is a capability gap that NAVs could fill in the future, then the Air Force should take the lead and begin a development and acquisition program to acquire a NAV. The technology challenges are very complex and diverse for such a small system. A focused development approach to a set of defined requirements would build synergy in the technical community to rapidly develop the subsystems required to achieve swarming NAVs. This is true not only for NAVs, but even for MAVs, if this class of air vehicle would fill the capability gap. Failure to define requirements and wait for the technical community to develop these systems to an ACTD level could lead to systems not optimized for Air Force missions. Thus, the Air Force needs to take the lead to make the future vision of NAVs come true!

Notes

[1]Department of Defense, *Unmanned Aerial Vehicles Roadmap 2002-2027* (Washington, D.C.: Office of the Secretary of Defense, December 2002), 41.

[2]Department of the Air Force, *Implications of Emerging Micro- and Nanotechnologies*, (Washington D.C.: Air Force Science and Technology Board [Committee on Implications of Emerging Micro-and Nanotechnologies], 2002), on-line, Internet, available from http://books.nap.edu/books/030908623X/html#pagetop, 183.

[3]Dora Marinova and Michael McAleer, Nanotechnology Strength Indicators: International Rankings Based on US Patents, *Nanotechnology*, no. 1 (Jan 2003), 14).

Appendix A

Round 1 Questionnaire

Instructions: Thank you for taking the time to participate in this survey. This survey asks for your educated opinion on when this technology will be available for use and to understand your reasons behind the forecast. You can provide a single year, a range of years, or even none if you do not believe the technology is feasible. The most important part of this section is to understand the reasons behind the forecast and what technological hurdles must be overcome. Your responses do not need to be focused on the technology. If you believe there are economic, environmental, or even ethical issues that must be overcome, then please feel free to express your opinion. Please feel free to use as much space as required. Your responses and participation are completely confidential. I ask that you complete the questionnaire and submit to me by email by Friday, 2 Feb, which is 2 weeks from today. If you have any questions at all about the questionnaire or need more time, please feel free to contact me at anytime. My email address is: William.davis@maxwell.af.mil or cell phone: 334-318-3639.

Question 1: When will swarming, nano-Unmanned Aerial Vehicles (UAVs), capable of performing direct attack missions be demonstrated in an operational environment? For clarity, I provide the following definitions.

> Nano-UAVs: Dimensions of <7.5cm defines the size of the air vehicle I am investigating. This dimension comes from the DARPA Defense Sciences Office Nano Air Vehicle Program. Please note I am not restricting the weight, propulsion method, speed, etc of the vehicle.
>
> Direct Attack Missions: The potential for small UAVs for intelligence, surveillance, and reconnaissance missions is obvious. This question seeks to understand the potential of these vehicles to be used in strike missions. Strike missions of any kind should be considered to include, anti-personnel, anti-aircraft, air-to-ground, indoor or outdoor, urban or desert regions for example.

Question 2: What are the major technological hurdles or areas that must be overcome to achieve this forecast? Or if you think this capability cannot be achieved, please provide the basis for your position.

Question 3: Please state, in your opinion, which of these technology areas is the most difficult to overcome and why?

Appendix B

Round 2 Questionnaire

General: The first round of this study asked participants a series of questions that asked the participant to provide a forecast for when the technology would be demonstrated in an operational environment, a position on the major technological hurdles that must be overcome to achieve this forecast, and which of these technologies will be most difficult to overcome and why.

The goal of the second round is to provide the participants with a synopsis of the results based on the inputs of all the participants and request each participant to make further arguments for their position or adjust their forecast based on new information brought up by other participants. In addition, several follow up questions are asked based on inputs from the responses. What I provide below is a summary of the average of the responses and these are highlighted in red print.

Please note I changed the order in which the questions are presented since I found asking the forecast question last makes more sense in light of understanding the positions on the technology hurdles that must be overcome to achieve this capability.

Question 2 from Round 1: What are the major technological hurdles or areas that must be overcome to achieve this forecast?

Summary response:

Power and energy requirements: The storage of energy and the conversion to propulsive power is very difficult in a system of this size. A 10 gram vehicle requires at least 1 Watt of power to stay up assuming 25% efficiency. This vehicle will require a high density energy storage that is also very efficient when transferred to propulsion and other uses. Batteries, fuel cells, and turbines are potential sources of power, but advances are required in all of these for a NAV to have sufficient range, speed, and payload for this mission profile. Current battery technology does not offer the required energy density and turbines at this scale are not sufficiently efficient for this mission profile.

Follow up question: Several participants mentioned the possibility of ‘biological’ fuel cells to store energy. What are your thoughts on research in this area? And would a ‘biological’ fuel cell provide enough storage and efficiency to power this size air vehicle?

Guidance, navigation, control mechanisms, and communications: The mission requirement to operate autonomously and in swarms requires the NAV to have sensors, communication, and processing capabilities that must be highly efficient and highly integrated into the air vehicle due to size, power and energy limitations. A large unknown in this area is the impact of the swarm requirement on the control system since work in this field requires considerable maturation before it will be usable. As one participant noted, a major limit to all very small vehicles is the

cubed-square law which results in energy density limited at small sizes since there is no place to put fuel or energy. Thus, solutions to the guidance, navigation, sensors, and controls problems must avoid the traditional relatively power hungry approaches to succeed.

Explosive technologies: Here a major hurdle is making use of a very small payload for some strike capability. One participant argued that the maximum payload for this size vehicle is restricted to about 20% of the GTOW. The DARPA vehicle is 10 grams which indicates only a useable 2 gram payload is possible if 20% is the constraint. Other participants also indicated a very limited to no strike capability for the 10 gram size air vehicle due to the extremely small size of the vehicle. A breakthrough in energetic materiel would be required to make this mission profile feasible.

Integration and miniaturization: The extremely small size and weight of the NAV leads to the requirement for advancements in manufacturing and subsystem packaging to achieve a high level of systems integration. The largest requirement for this is in the guidance, navigation and control systems.

Round 1 Question 3: Please state, in your opinion, which of these technology areas is the most difficult to overcome and why?

Summary response:

The responses to this question were quite varied and statistically a mean was not relevant. Perhaps a larger sample would have achieved this but that will not be possible at this time. The technology area that was listed the most was guidance and navigation technology area followed closely by the explosive technology. The requirement for autonomous swarming operations posed the largest hurdle due the previously noted state of swarming research for these types of operations. Participants further stated the guidance and navigation problem is made even more difficult due to the low energy requirement that constrains the system due to the limitations in that technical area. However, the responses implied the energy/power problem could be overcome for this size air vehicle.

As stated before, most participants had doubts this size air vehicle would be operationally useful due to the very small payload size possible. One thing was clear in all but one response, the DARPA size air vehicle should not be a problem to achieve, i.e. fly. The problem lies in an operationally useful vehicle that is capable of handling the autonomous and swarming strike mission profile with a useable payload.

Follow up question: For this round I ask each participant to reevaluate which technical area poses the largest hurdle to achieve the mission profile for the NAV? Is it the guidance, navigation, and communication systems or the payload or warhead system?

Round 1 Question 1: When will swarming, nano-Unmanned Aerial Vehicles (UAVs), capable of performing direct attack missions be demonstrated in an operational environment?

Summary Response

The average response was a forecast of 10 years for operational vehicles capable of cooperative behavior with payloads useful for some 'limited' attack missions. No real definition of 'limited' was provided. Most respondents qualified their forecast since there will be limitations on the operational range of the vehicle due to the obvious tradeoffs that have to be made for endurance, speed, and payload. However, one dissenting view argues that these types of operational missions will never be attainable since the technical hurdles are too large for providing sufficient power to allow useful mission duration with useable payload in a 7.5cm class machine.

To stimulate more discussion, I will inject some more discussion on possible strike missions these vehicles could be used for even with a small payload which some respondents discussed.

Follow up question: Do you think it would be possible to use NAVs in an anti-personnel role using limited directed energy impact (i.e. like a bullet)? Several respondents mentioned the ongoing research in smart bullets in a ballistic profile. What I am asking is similar but still using NAVs in cooperative engagements in this type of scenario albeit at much less speed than a ballistic projectile.

Follow up question: Could you see NAVs delivered to a region much like a cluster munitions then released to autonomously attack programmed targets? This is similar to the Sensor Fused Weapon currently in the USAF inventory. This is essentially a series of smart sub-munitions that are delivered to a region by aircraft. These sub-munitions then maneuver over the region to identify various targets then attack when a target is identified using a shape charge specific to the target type. If a target is not identified, then the sub-munitions go inert and fall to the ground.

Follow up question: Based on the discussions above, do you think an NAV could be operational in this mission scenario within 10 years?

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